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STUDY AND FLIGHT TESTS OF A MACH 5 EXPERIMENTAL RAMJET

Roger Marguet

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CONTENTS

NOTATIONS

Symbols

M; local Mach

p: pressure

A: area

T: temperature in ^{o}K

$[A5D5]$: exit dynalpy [momentum-flow]

$[AoDo]$: entrance dynalpy

$\dot{m}_o$: air flow per second

$\dot{m}_k$: kerosene delivery per second

q: kinetic pressure $\frac{1}{2}pV^2$

φ: injected fuel-air mixture

Secondary symbols

a: speed of sound

x: drag

o: upstream infinity

1: at outlet of antechamber

2: upstream of combustion chamber

3: in chamber

4: at throat

5: at the end of combustion

i: isentropic

i': stagnation downstream from the shock

g: internal

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ABSTRACT

Studies and research on high speed atmospheric propulsion have lead O.N.E.R.A. to experiment in flight with ten ramjet missiles. This operation received the code name of "STATALTEX."

Four missiles reached a flight speed of nearly 4,600 feet per second, i.e., about Mach 5, between the altitudes of 40,000 to 115,000 feet.

In this paper the information obtained in the course of this study are described and theoretical predictions and experimental results are compared. The knowledge acquired permitted us to obtain useful data applicable to an eventual atmospheric booster able to reach Mach 5.

Introduction

In the field of research concerning missile propulsion at high supersonic speeds, ONERA initiated a program of studies and tests in 1960 on the subsonic combustion ramjet capable of operation up to Mach 5 and using kerosene as fuel. This program was aimed at use in possible fast vehicles with atmospheric trajectory, subsonic aircraft, and long-range low-trajectory missiles. This mission was completed in April 1964. /5*

Ten experimental missiles were fired. Among them, four accelerated to speeds approaching Mach 5 and three others exceeded Mach 4.5.

For reasons of economy and simplicity, no guidance was provided on board these missiles. There was consequently a certain spread of trajectories. Attempts were made to limit this dispersion by reducing the causative contingent factors - duration of booster propulsion, wind, percussion on leaving the launcher.

*Numbers given in margin indicate pagination in original foreign text.

Attempts to carry maximum performance of Stataltex beyond Mach 5 failed, since the ramjet was not inserted at nominal conditions required in the very narrow acceleration corridor.

The ramjets, with average mass of 275 kg, were separated at a speed close to 1000 m s^{-1}. A Stromboli booster comprised the accelerator stage.

Performance was below that of an engine with optional variable geometry, the entrance and exit geometry of Stataltex being fixed. A compromise study in the investigated speed range led us to adapt the air intake and the ejector to a flight Mach number of ~3.5. Under these conditions the air intake functioned in superadaptation beyond this flight speed.

A telemetering system--28 measured parameters, 15 of which were thermal measurements--as well as a trajectographic system made possible analysis and workup of data of essential phases of these experiments, in particular:

- comparison of the propulsion balances established by stationary and in-flight studies,
- knowledge of this balance near Mach 5; these flight conditions not being reproducible at the test bench,
- justification of a technology for the ramjet used as accelerating motor up to Mach 5.

I. HISTORY OF THE STUDY /6

Two essential phases of activity were the product of the initiation of operation STATALTEX at ONERA

- a general research activity and analytical studies,
- a synthesizing activity in the course of which ten experimental missiles were fired.

The first phase concerned the following requirements.

Thermodynamics

Establishment of ramjet performances up to Mach 5 with computerized calculation program

Propulsion

Combustion tests with simulation of conditions of internal operation in the range of speeds 3<M<5. In this connection, several cellules of the ONERA aerothermodynamics laboratory (Palaiseau) were equipped with a kerosene air heater with oxygen delivery, reproducing approximately the conditions of temperature at M_0=6, but not the composition (Specifically, presence of H_2O and CO_2).

Tests of kinetic heating with development of burners and test devices making possible the simulation of fluxes of 2000 kW/m^2.

Utilization for the first time in France of Stromboli solid-fuel propellants, developed in collaboration with the Société d'Etudes de la Propulsion par Réacteur (SEPR -- Society for the Study of Jet Engine Propulsion).

Aerodynamics

Study of the operation of an isentropic air intake adapted to $M_0 = 3.5$ in the range M3 to M6.

External aerodynamic study in moderated hypersonic conditions.

Materials

Development of thermal protective means using ablation.

Bophenal and Orthostrasil for the ejector, phenolic resin with endothermic additives for external protection.

Flight dynamics

Use of computer programs for study of corrections of trajectory (wind, percussion, aeroelasticity).

Measurements

Development of apparatus related to operation Stataltex (pickups, flowmeters, on-board thermometric instrumentation, use of telemetering in ambient conditions of high temperature and pressure)

The second phase extends over three periods /7

1st: missiles designated STX 01, 02, 03, 04.
2nd: performance test missiles designated STX 05, 06, 07, 08
3rd: missiles for speeds above $M_o = 5$ STX 09 and 10

Table I recapitulates the history of Stataltex flights and summarizes the results.

TABLE 1. CHRONOLOGY OF TEST FLIGHTS--OVERALL RESULTS.

Period	Engine No.	Date of firing	Place of firing	General characteristics: booster	Results: General behavior	Results: Measurements	Results: Achieved performances
1st period	1	Nov. 1960	C.E.R.E.S. (France)	Stromboli 180,000 daN.s	Correct End of propulsion due to heating of flame tube	Telemetering to t = 32 sec	$V = 1230\ m\ s^{-1}$ $Z = 13\ km$ $t = 32\ s$
1st period	2	Nov. 1960	C.E.R.E.S. (France)	Stromboli 180,000 daN.s	Correct Engine lost at t = 46 sec	Telemetering to t = 39 s Cinetheodolites ended 46 sec	$V = 1444\ m\ s^{-1}$ $Z = 18.8\ km$ $t = 46\ s$
1st period	3	May 1961	HAMMAGUIR (Sahara)	Stromboli 180,000 daN.s	Accident at separation (pumping air intake)	No internal measurements (breakdown of recording instrument)	$V = 1115\ m\ s^{-1}$ $Z = 5.95\ km$ $t = 20\ s$
1st period	4	May 1961	HAMMAGUIR (Sahara)	Stromboli 180,000 daN.s	Accident at separation (pumping air intake)	Telemetering to t = 17.6 s	$V = 1160\ m\ s^{-1}$ $Z = 8\ km$ $t = 19.4\ s$
2nd period	5	Dec. 13, 1961	C.E.R.E.S. (France)	Stromboli 180,000 daN.s	Correct Combustion to 40 km altitude	Telemetering to impact t = 200 sec	$V = 1360\ m\ s^{-1}$ $Z = 40\ km$ $t = 70\ s$
2nd period	6	Dec. 9, 1961	C.E.R.E.S. (France)	Stromboli 188,000 daN.s	Correct Combustion to expenditure of fuel	Telemetering to impact t = 215 sec	$V = 1480\ m\ s^{-1}$ $Z = 29.7\ km$ $t = 61.5\ s$
2nd period	7	July 9, 1962	C.E.R.E.S. (France)	Stromboli 188,000 daN.s	Correct End of propulsion due to rupture of flame tube kinetic heating	Telemetering to impact	$V = 1360\ m\ s^{-1}$ $Z = 11.5\ km$ $t = 32.5\ s$
2nd period	8	July 9, 1962	C.E.R.E.S. (France)	Stromboli 188,000 daN.s	same as 7	same as 7	$V = 1475\ m\ s^{-1}$ $Z = 13.7\ km$ $t = 38\ s$
3rd period	9	Oct. 8, 1963	C.E.R.E.S. (France)	Stromboli 188,000 daN.s	Correct same as 6	Telemetering to t = 28 sec	$V = 1490\ m\ s^{-1}$ $Z = 11.8\ km$ $t = 46\ s$
3rd period	10	Apr. 23, 1964	C.E.R.E.S. (France)	Stromboli 200,000 daN.s	Rupture before separation	Telemetering ended 19 sec	

II. THE COMPOSITE STATALTEX MISSILE

II.1 General definition

/8

The Stataltex missile comprises two stages, a solid fuel stage--the booster--whose mission is to bring the ramjet to its self-sustaining velocity, near 1000 m per second, and the experimental stage comprising the ramjet.

The total mass at launch is of the order of 1600 kg, of which 300 kg is for the ramjet, and the total length of the missile at launch exceeds ten meters. The missile has no guidance equipment. Figures 1, 2, 3 and 4 present certain diagrams and views of the missile in order of firing.

Various configurations were flight tested: the table on the following page summarizes their characteristics.

II.1.1. Acceleration stage

This is a Stromboli plastolite powder booster. Its total impulse varied between 180,000 and 200,000 decaNewtons, depending upon the nature of the test.

Duration of combustion, 20 sec, is fixed with a tolerance of ± 1 sec to reduce the spread, since the engine is not piloted.[1]

II.1.2. Separation of the two stages

Assembly was effected by explosive bolts, an inertial switch giving the separation command.

Inclination at separation is the essential dispersion factor.

The following precautions were taken to limit the causes of the spread:

- tolerance on the duration of combustion of the block of powder (II,1.1)
- site of the launcher, taking into account an aerological sounding before firing (modulus and direction of the wind)
- account taken of the elasticity of the launcher.

II. 1.3. The ramjet

This is a truncated conical ramjet made of refractory steel, with subsonic combustion (figures 4 and 5). Air intake and ejector are of fixed geometry.

The combustion chamber is supplied with kerosene. Pneumatic devices ensure the flow and distribution of the fuel.

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[1]A bomb test of a sample of the charge utilized allowed determination of the dimension of the ejector in each flight propulsion device, to obtain combustion duration of 20 sec.

TABLE 2. CHARACTERISTICS OF THE STATALTEX MISSILES.

Missiles No.	Mass (kg)	Length (m)	Fuel on board	Air/fuel injection (1) $K_g(s^{-1})$	(2) φ	$A_1(cm^2)$ intake section	$A_4(cm^2)$ sonic section	$A_5(cm^2)$ divergent outlet	Flame tube protection[1]	Air intake[2]	Measurements
1	263	5.2	481	0.9	0.85	543	415	1308	A.L.K.S.[3]	Isen-tropic R260	ONERA telemetering 3 continuous data 10 intermittent data no temperature measurement
2	268	5.2	481	0.90	0.85	543	415	1308	4 mm[4] Bophénal	"	ONERA telemetering 3 continuous data 10 intermittent data no temperature measurement
3	265	5.2	481	1	0.85	543	415	1308	6 mm Bophénal	"	ONERA telemetering 3 continuous data 10 intermittent data
4	259	5.2	481	1	0.85	543	415	1308	6 mm Bophénal	"	5 channel record-ing
5	267	5.2	481	1.10	1	543	415	1308	8 mm Bophénal	R280	ONERA telemetering 3 continuous data 21 intermittent data, of which 11 temperature

TABLE 2. CHARACTERISTICS OF THE STATALTEX MISSILES (CONTINUED).

Missiles No.	Mass (kg)	Length (m)	Fuel on board	Air/fuel injection (1) $K_g(s^{-1})$	(2) φ	$A_1(cm^2)$ intake section	$A_4(cm^2)$ sonic section	$A_5(cm^2)$ divergent outlet	Flame tube protection[1]	Air intake[2]	Measurements
6	275	5.2	481	1.20	1	543	394	1576	8 mm Bophénal	R280	ONERA telemetering 3 continuous data 21 intermittent data, of which 11 temperature
7	275	5.2	481	1.40	1	543	394	1576	8 mm Bophénal	R293	
8	279	5.2	481	1.40	1	543	394	1576	8 mm Bophénal	"	
9	275	5.2	481	1.3	1	543	394	1576	Ortho-strasil[5]	"	ONERA telemetering 3 continuous data 26 intermittent data, of which 17 temperature channels
10	300	5.6	751	1.3	1	543	394	1576	Ortho-strasil	"	

(1)--Maximum injected flow
(2)--Maximum projected air/fuel mixture

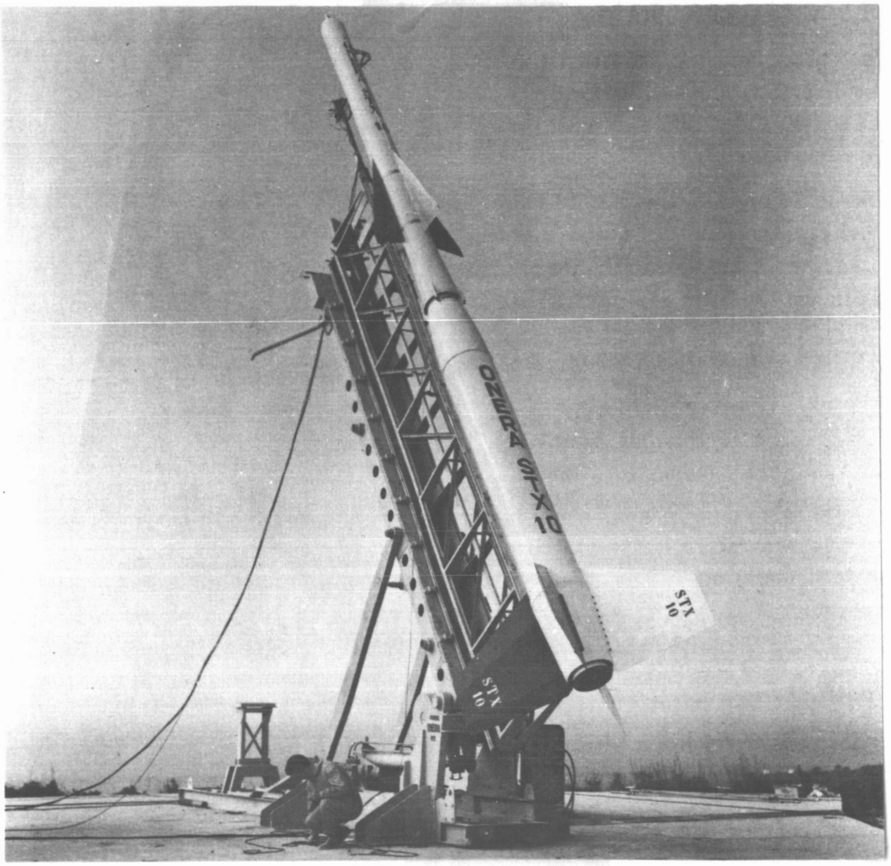
[1]Thickness of throat.

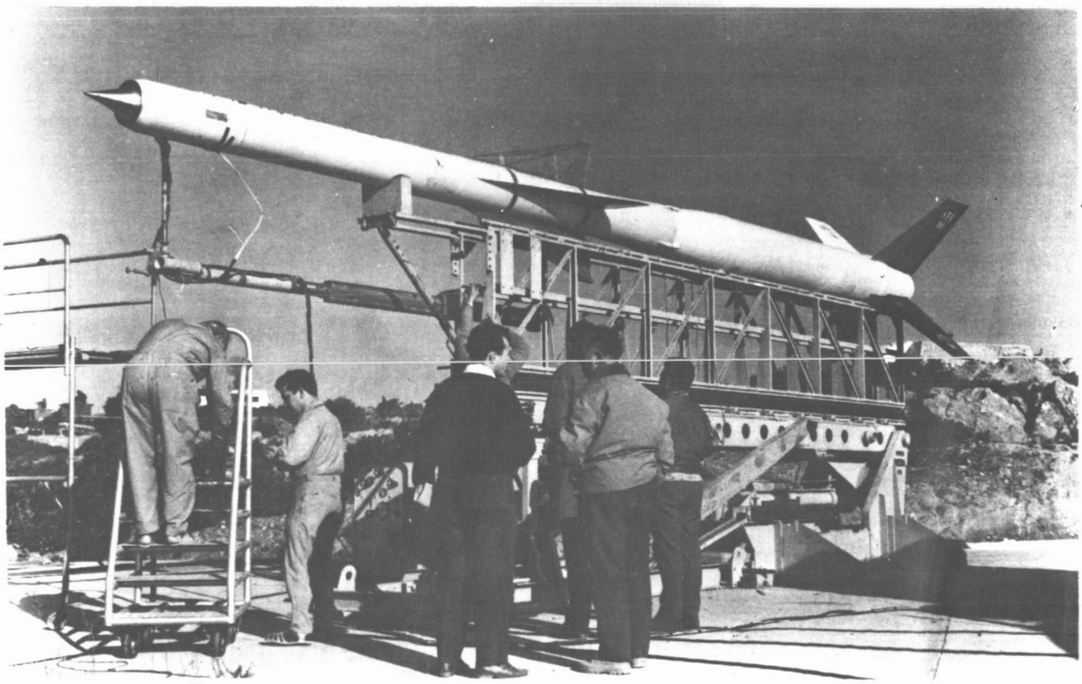
[2]Catalog reference air intakes.

[3]Protection constituted by a mixture of water, alumina and kaolin.

[4]Endothermal-effect protection constituted by boric anhydride, phenolic resin and alumina.

[5]Laminate consisting of phenolic resin and silica fabrics manufactured by Sud Aviation.





Figures 1 and 2. Composite missile on the launcher.

The central body contains the load of measuring, control and injection apparatus.

The characteristics of the combustion chamber result from a compromise to satisfy the following conditions:

- maintenance of cruising speed corresponding to Mach 5 at altitudes of 25 or 30 km
- ensuring acceleration sufficient for separation velocity of the order of $10\ m\ s^{-2}$.

The antechamber. The antechamber is of the classic pilot chamber type. This one traps 10 percent of the flow swallowed by the air intake.

Injection is effected by spraying onto the flame holder. Figures 6 and 7 show the embodiment of these assemblies. The pyrotechnic igniters with electric fuses control the ignition of the combustion chamber two seconds before release of the ramjet fuel (fuel admission at that moment).

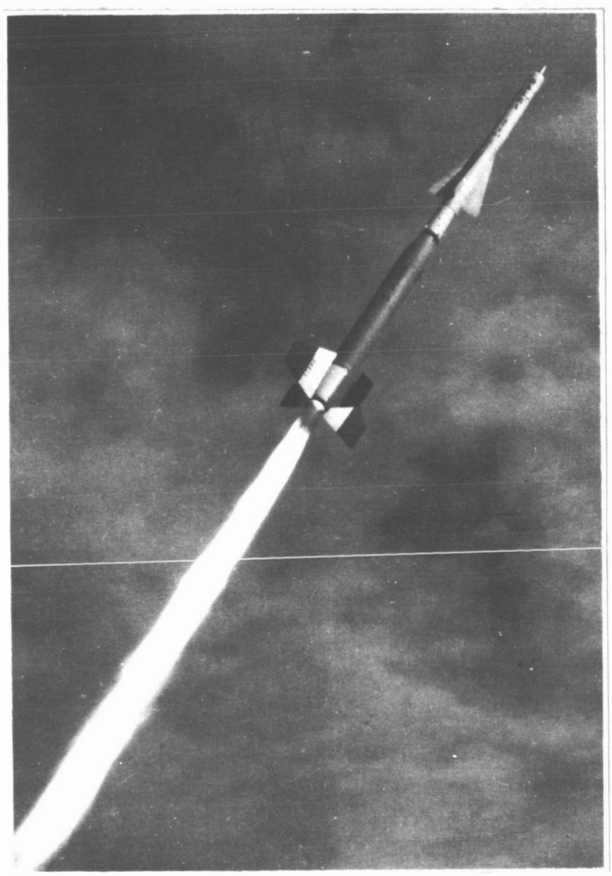
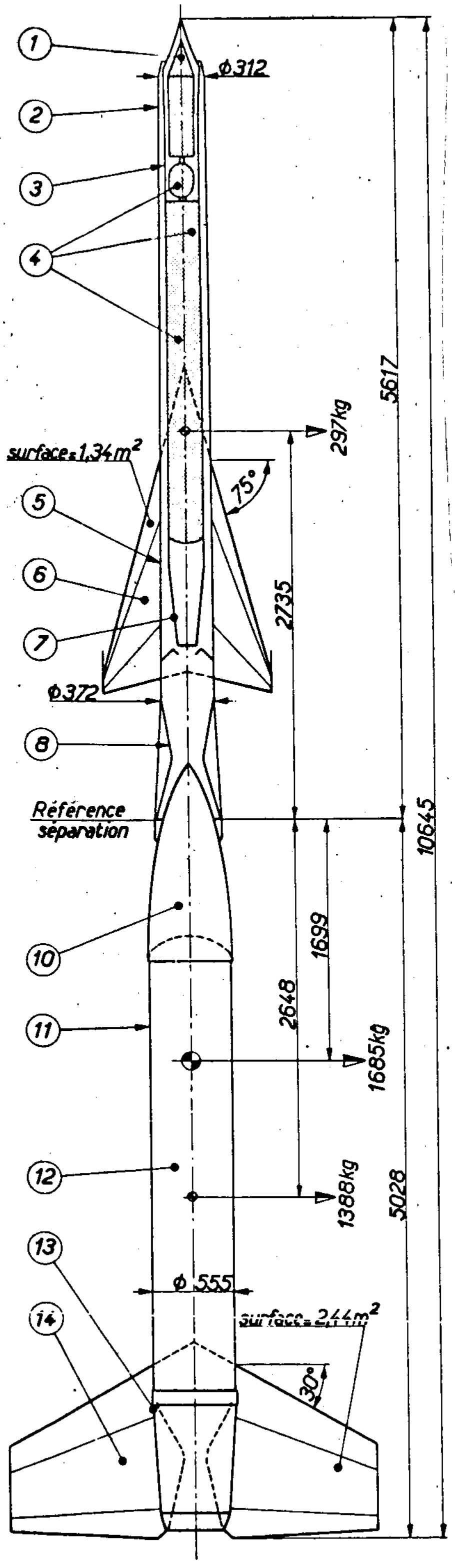
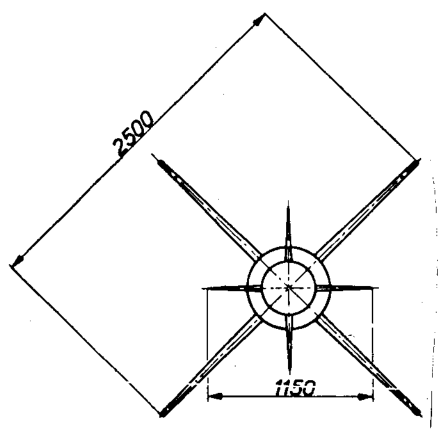


Figure 3. Composite missile in flight.



STATALTEX			
Ref.	Designation	Weight	G
1	Point - telemetering	29.4	4944
2	Shell	34.5	3855
3	Main body	20	4188
4	Tank - injection - fuel	93.35	3196
5	Undercarriage	26 4	1562
6	Stabilizers	28	1515
7	Engine	18.25	1627
8	Flame tube	42	571
9	Protection -- bolts	5.1	2732
BOOSTER			
10	Booster-ramjet connection	51	452
11	Propellant body	180	3011
12	Block of plastolite powder	1042	2495
13	Rear drum	39	4431
14	Stabilizers	76	4520



Position of stabilizers

Figure 4. Composite assembly STATALTEX No. 10.

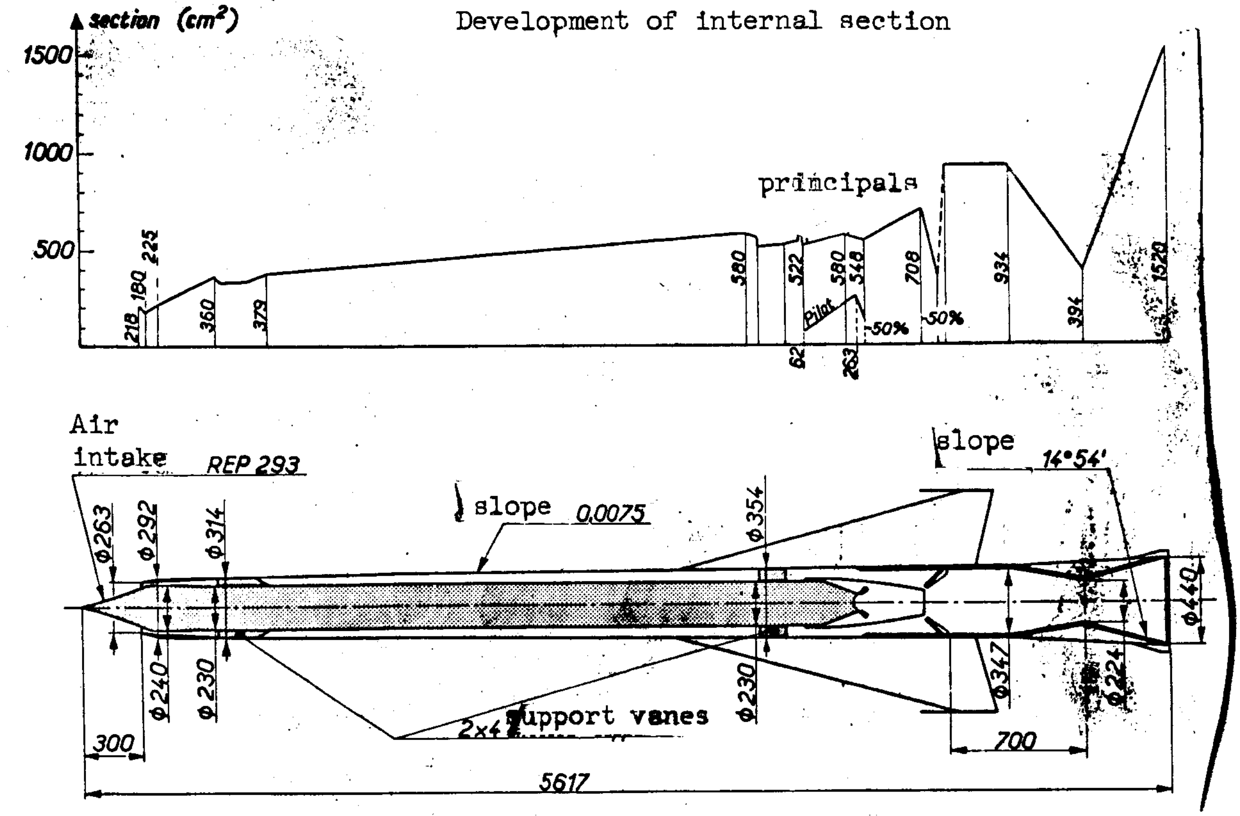


Figure 5. Internal geometry.

The injector. It comprises a pneumatic circuit and a hydraulic circuit. /13

The pneumatic circuit sends air compressed at 25 bar into a piston reservoir which contains the fuel. This air, stored at a pressure of 250 bar, is released by a remote-controlled valve by means of an automatic switch, and supplies an expander.

A mixture limiter constitutes an essential element of the hydraulic circuit.

This device, of simple design and regulated precision, has the effect of restraining fuel flow by means of an adjustable blocking of the circuit when the latter tends to exceed the value corresponding to the maximum permissible air-fuel mixture.

The fuel flow, measured by a linear diaphragm flowmeter, is compared to the air flow, function of $(p_i' - p_0)$.

This makes it possible to maintain the mixture at a predetermined value (less than unity) while setting the flow controls for a ratio of 15 to 1.

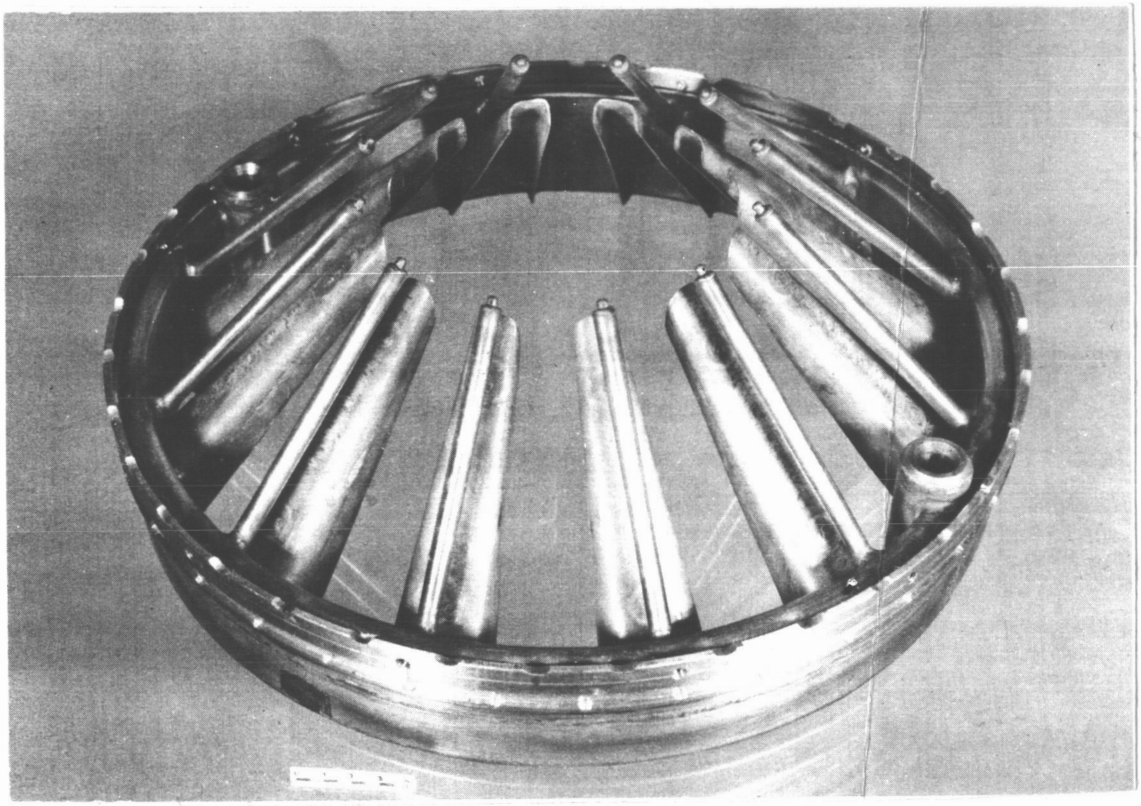


Figure 6. Flame holder and injectors of the main circuit.

Figures 8 and 9 present an overall diagram and general view of the injection device. Figure 10 is a schematic view of the antechamber. /14

Thermal protection of the flame tube and the ejector. The thermal problems entailed in the case of the high-speed ramjet are certainly the most difficult to solve. /17

Combustion chamber and frame are subjected to internal and external fluxes that are very sizable. The fluxes at the throat of the ejector may reach 2500 kW/m^2 in flight.

Two solutions for thermal protection were developed and tested on the flight engines, namely Bophenal and Orthostrasil (figure. 11). The Bophenal coating was prepared by ONERA. The Orthostrasil flame tubes were built by Sud-Aviation.

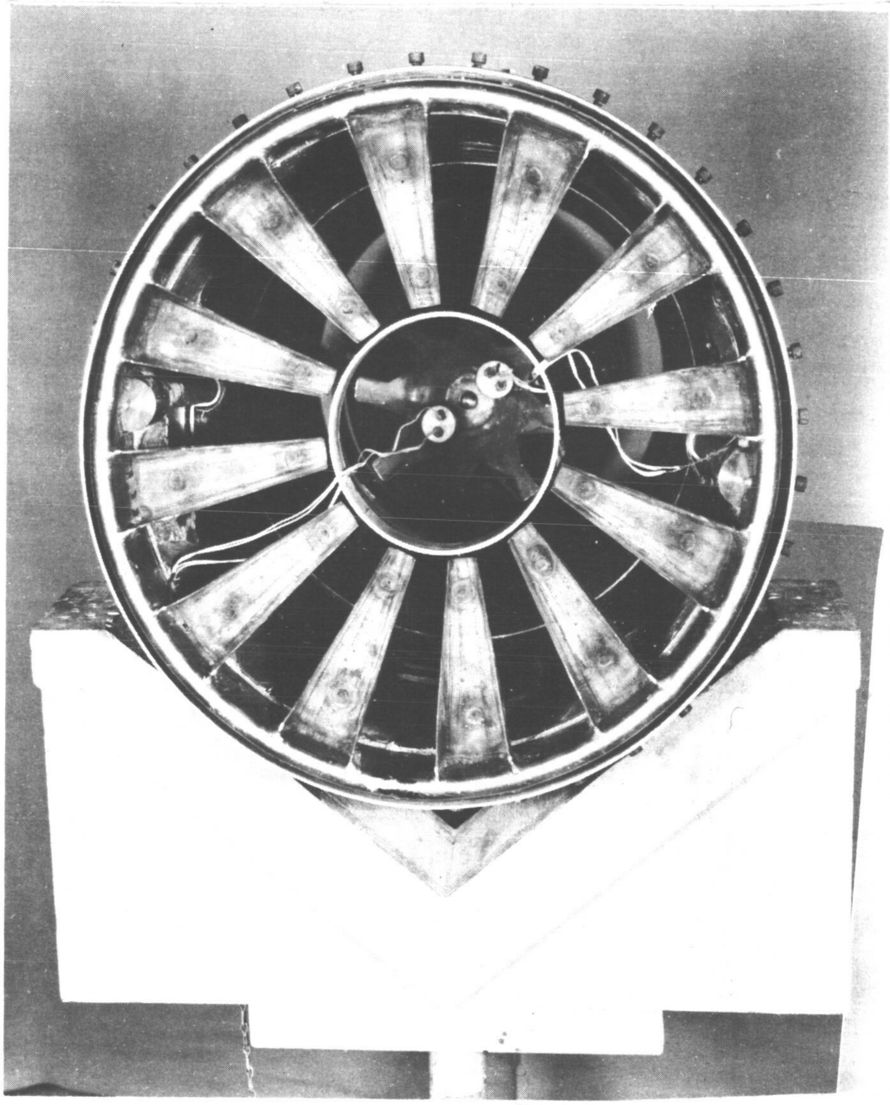


Figure 7. Flame holder, injectors and pilot chamber, flame tube disassembled.

II.2. Law of flight of the Stataltex missiles

The missile trajectory is "unguided." Ramjet altitude and speed depend upon two essential variables, the engine geometry being fixed, namely:

- inclination of the trajectory at the instant of separation
- injection furnished by a mixture limiter which ensures a practically constant regulation, the injected flow not being able to exceed a maximum determined before firing.

Figures 12 and 13 show several trajectories and flight speeds achieved in Stataltex firings.

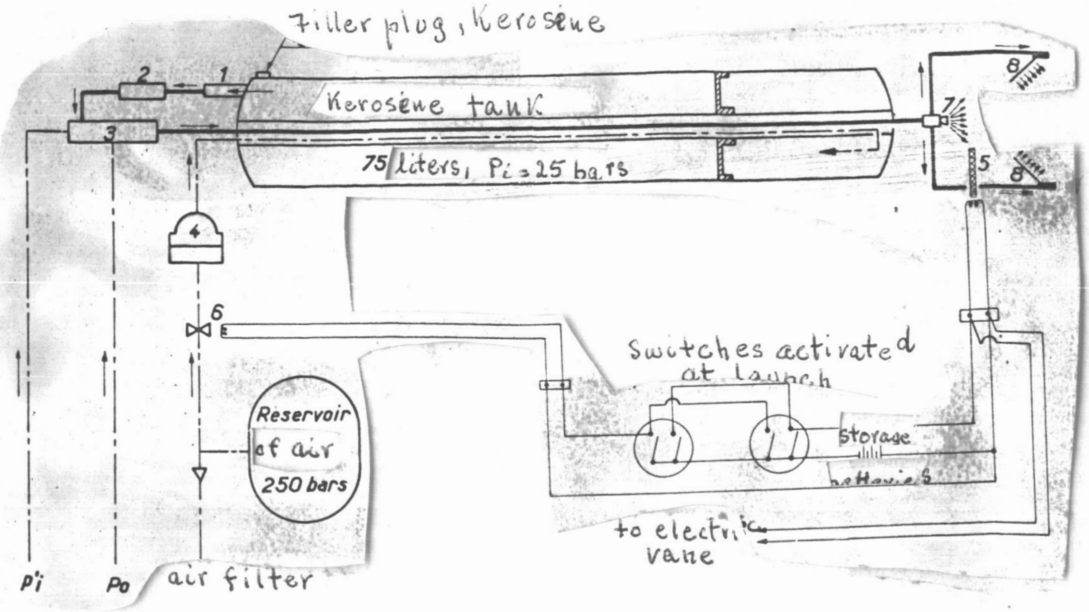


Figure 8. Principle, injection circuit. 1. Spark cap and filter; 2. flowmeter; 3. mixture limiter; 4. expander; 5. bouchet igniter; 6. fuse valve; 7. pilot injector; 8. main injector.

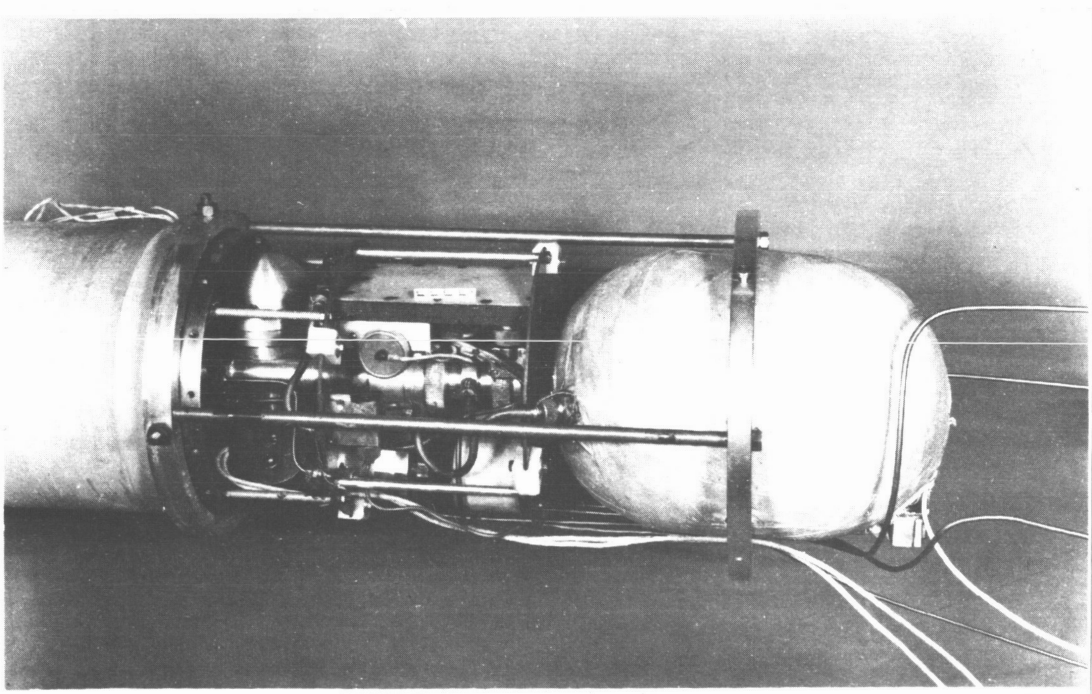


Figure 9. Injection assembly.

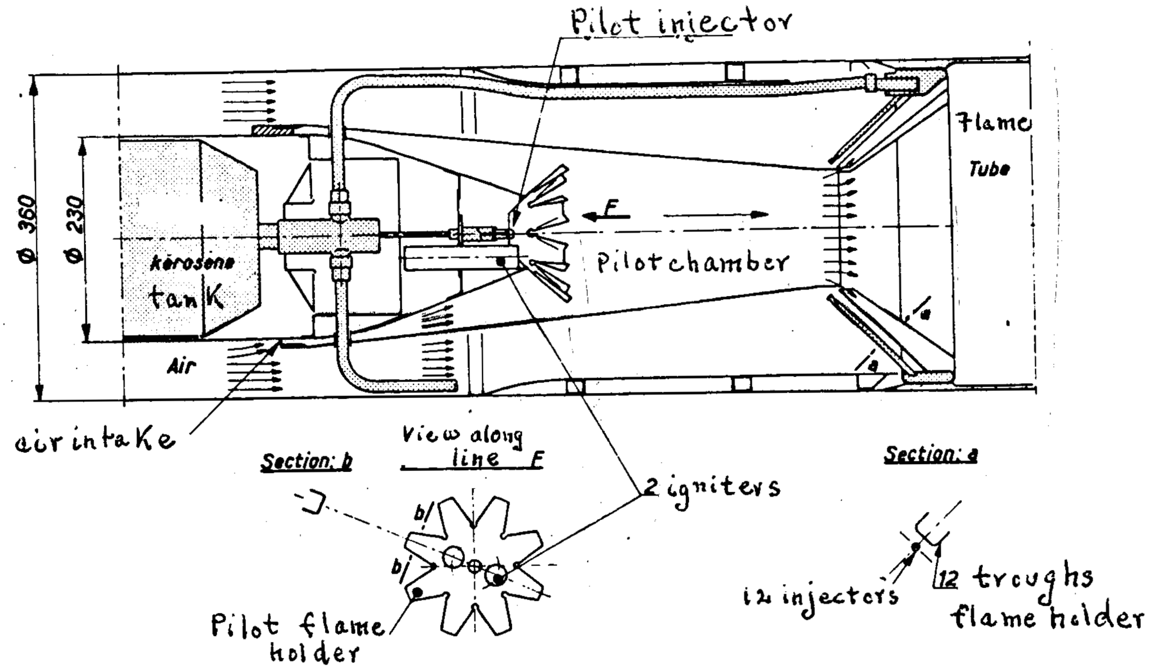


Figure 10. Characteristics of the Stataltex No. 10 engine.

Figure 14 shows, for a given flight configuration, the influence of the inclination of the trajectory at separation upon missile performance.

Maximum accelerations do not exceed 30 m sec^{-2} (fig. 15). /19

The different sequences of a firing are as follows:
1. Composite flight. Launch site is variable, inclination about 60°. Propulsion of the first stage lasts 20 seconds, separation altitude being around 6 km. The ramjet is ignited before separation. The remote-control valve, actuated by electric fuses and switch system, releases compressed air for purging the fuel. Another valve controlled by the same switching system releases the kerosene circuit two seconds after separation.
2. Ramjet flight. The self-sustaining stage then accelerates to maximum speed of 1500 m sec^{-1}; flight altitude may vary according to inclination at separation, so that the apogee is between 15 and 40 km. Duration of propulsion does not exceed 60 seconds, and depends upon the type of trajectory and the on-board mass of fuel (Table II)
3. Ballistic flight. Range may attain 250 km, the total duration of the flight being of the order of five minutes.

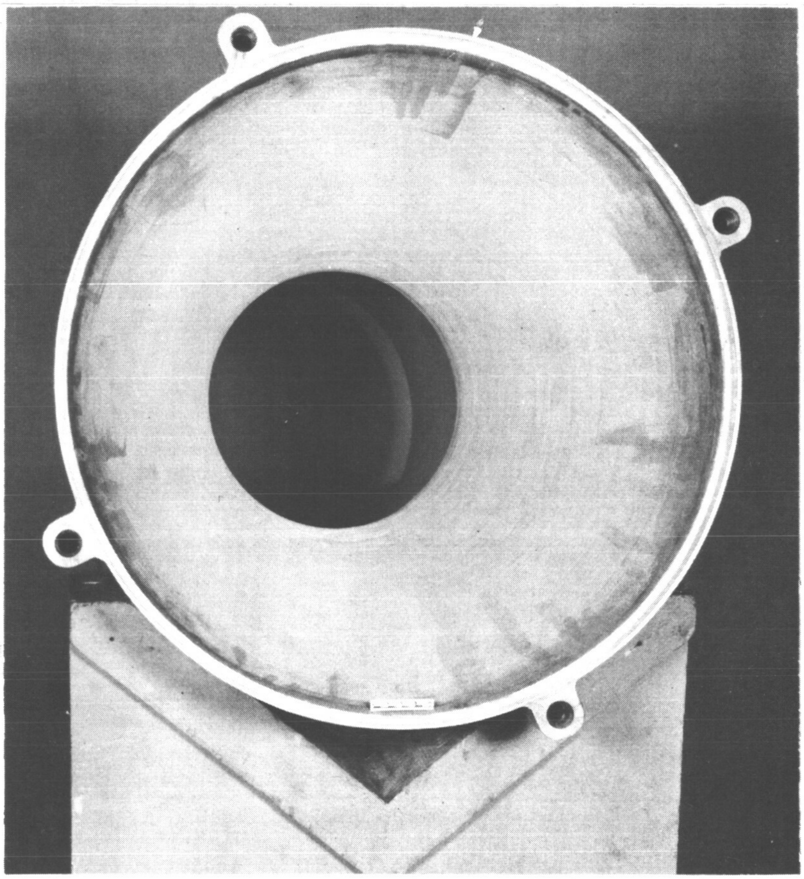


Figure 11. Orthostrasil ejection nozzle.

III. Actual performance

III. 1. Measurement program

Use of an assembly of means for internal and external measurement which is relatively precise has allowed quantitative workup of certain data which yield the value of the operational parameters of the missile.

Most of the Stataltex missiles were equipped with a S.F.I.M./O.N.E.R.A. telemetering system, transmitting on 101 MHz (missile No. 4, fired at Hammaguir, had a photographic recorder).

A pressurized and heat-shielded container held the measuring unit (transmitter, pickups and accessories). See Figure 16.

The amount and type of data transmitted to the ground varied from test to test. By way of example, Figure 17 shows the program of internal measurements concerning Stataltex firing No. 10.

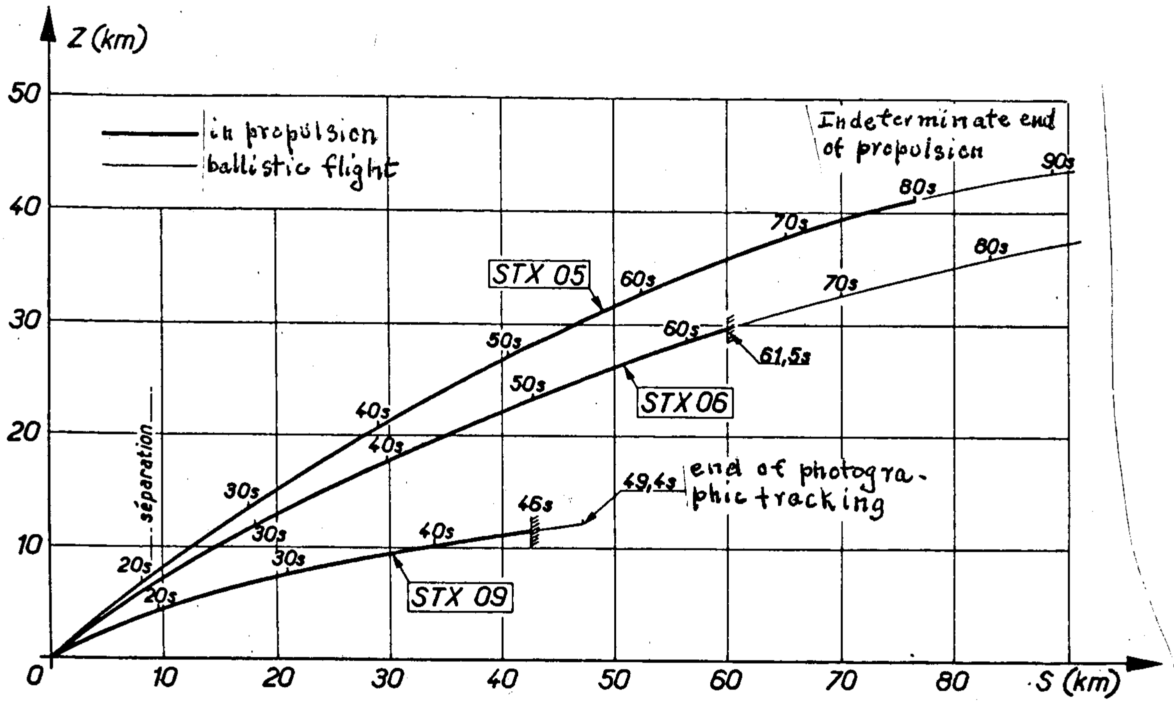


Figure 12. Trajectories, Stataltex in flight.

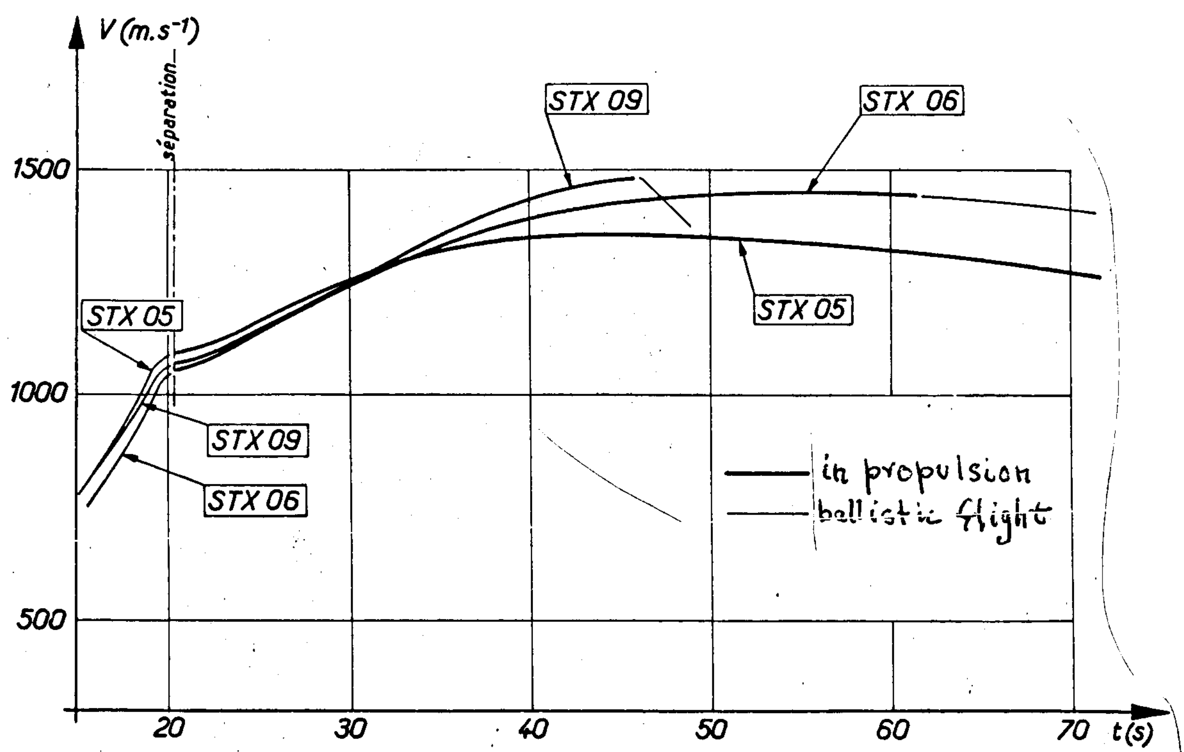


Figure 13. Laws of velocities achieved in flight.

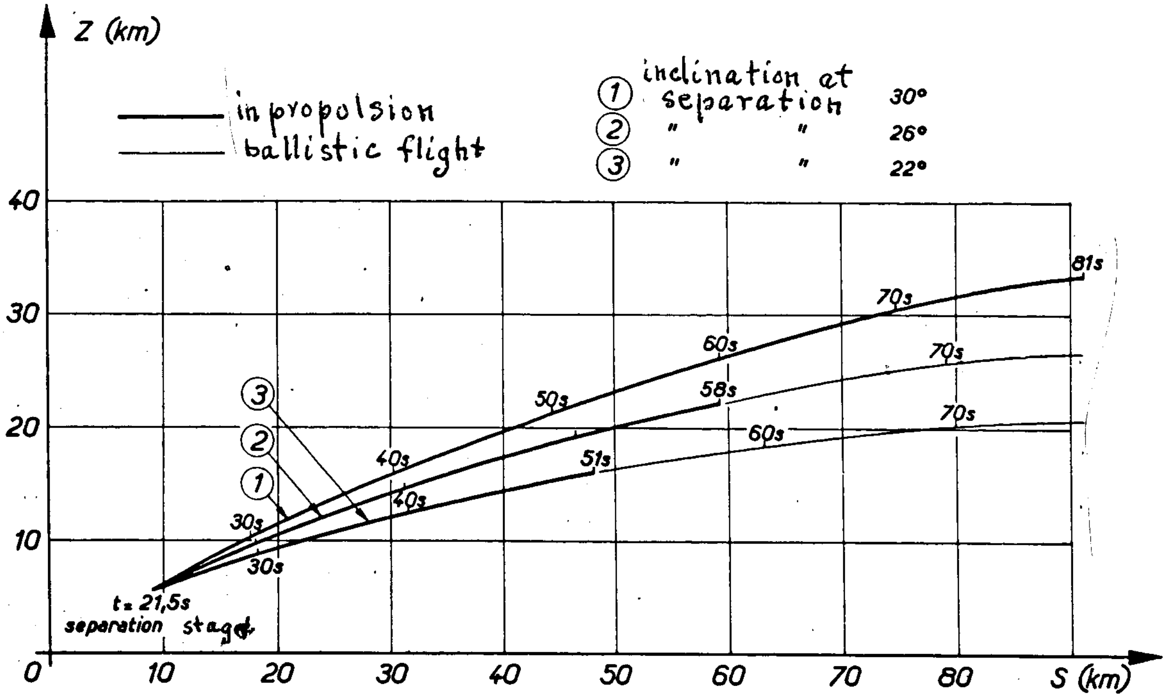


Figure 14. Dispersion of trajectories in flight. (Influence of inclination at separation mass of fuel on board 37.5 kg)

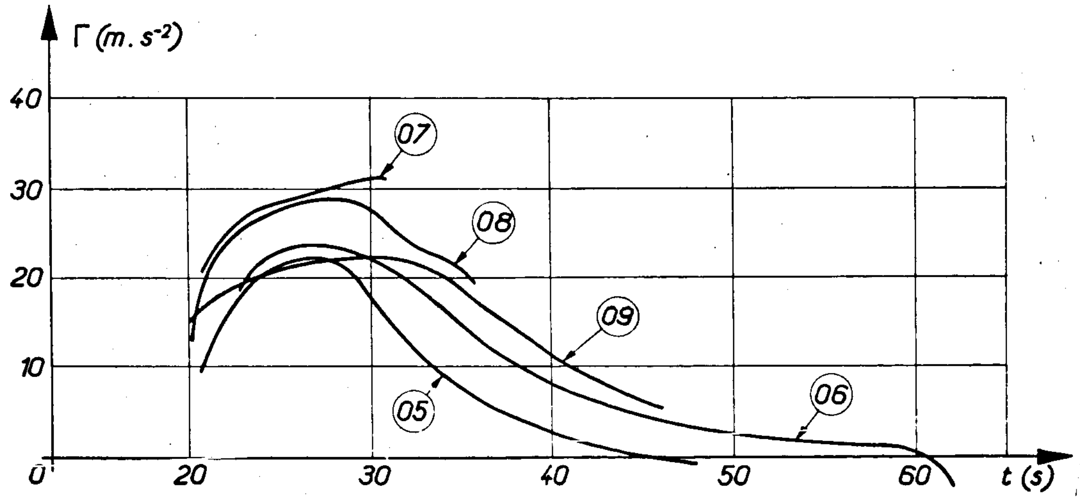
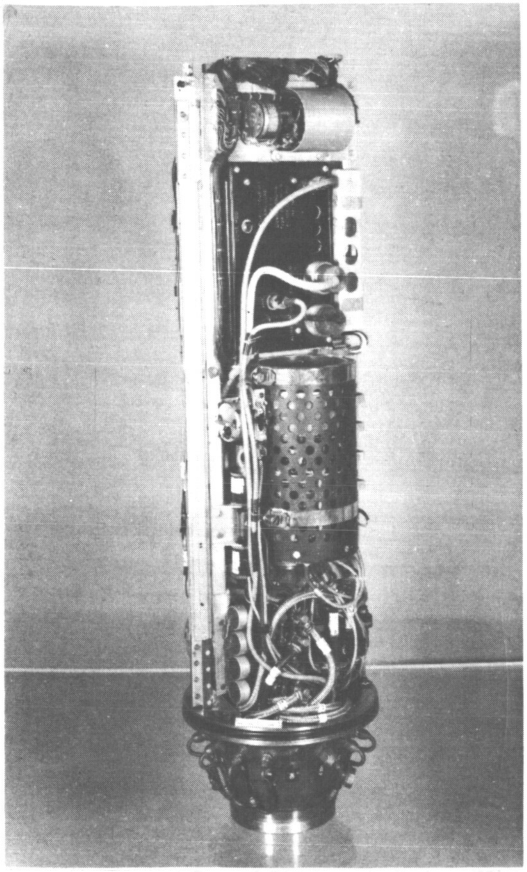
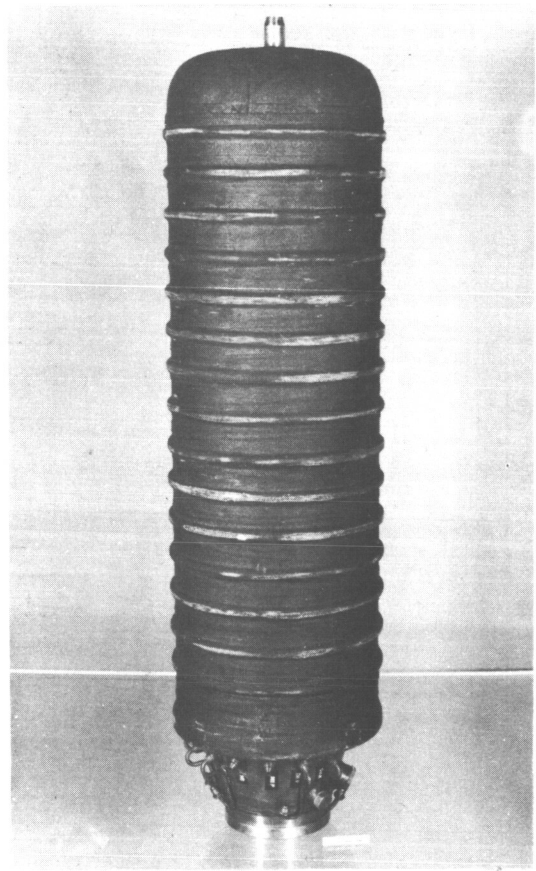


Figure 15. Accelerations. (Average values according to telemetering accelerometer)



Measuring cradle.



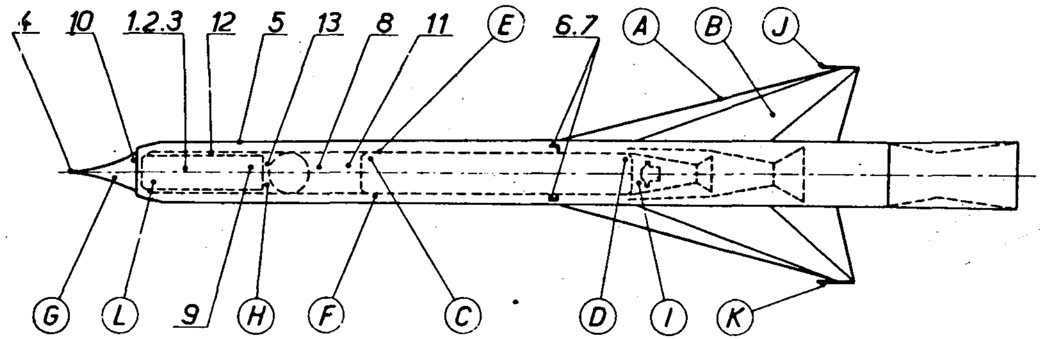
Measuring cradle in its pressurized container.

Figure 16.

This program comprised recording of 21 sets of data:

- 2 continuous
    - longitudinal acceleration
    - injected kerosene flow
- 19 intermittent
    (3 readings per second, per datum)
    - Normal accelerations
    - impact pressure
    - external static pressure
    - two static pressures at the end of the diffuser
    - static pressure at the head of the diffuser
    - injection pressure
    - telemetered ambient pressure
    - ten measurements of temperature (wall and flow)

The telemetering transmitter permitted the plotting of the trajectory with use of a suitable infrastructure (ONERA trajectographic procedure).



Temperatures

A. Leading edge of airfoil
B. covering of airfoil
C. fuel tank (forward)
D. fuel tank (aft)
E. wall central body
F. wall central body symmetrical
G. Ambient temperature, forward point
H. Ambient temperature, central body (aft telemetered)
I. Ambient temperature, aft fuel tank
J. Stagnation temperature. Airfoil probe
K. Stagnation temperature. Airfoil probe
L. Internal temperature, frame, telemetered[1]

1. Longitudinal accelerometer (2 sensitivities)
2. Normal accelerometer
3. Transverse accelerometer
4. Pi-Ps (2 sensitivities)
5. Ps
6. Internal flow pressure
7. Internal flow pressure (2 sensitivities)
8. Injection pressures
9. Pressure, telemetering compartment
10. Static pressure on point
11. Flowmeter
12. Forward diffuser pressure
13. Internal pressure, forward central body

Figure 17. On board measurements, Stataltex No. 10.

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[1]Thermistor: the other measurements by chromel-alumel thermocouple.

Maximum errors occurring in workup of the results are summarized below. /21

Parameter		Error
Telemetered pressures		2 percent
Telemetered fuel flow		3 percent
Telemetered accelerations		0,5 m s^{-2}
Speed (moving pictures theodolites, trajectograph)		±5 m s^{-1}
Altitude		±50 m
Weather sounding	pressure	±2 mb
	temperature	±2° C

III, 2. Comparison between predicted and actual firing performance

This study is based on the in-flight evolution of the following magnitudes:

- conventional thrust
- specific impulse
- internal pressures deduced from data transmitted during flight and data from a fixed point
- efficiencies of ejector and combustion measured at the ONERA and LRBA combustion tunnels
- theoretical values of internal and external drag coefficients adjusted with wind-tunnel tests
- characteristics of air intake

Efficiency of the ejector

The value of this efficiency was measured on the Stataltex, full-scale, temperature of the ejector being about 2000° K. Dissociations were thus negligible in these temperature conditions.

Combustion efficiency

Studies and tests made on the combustion test bench at ONERA in the range of speed passed through during flight furnished the average mathematical relationship presented in figure 18. /22

We note however that the pressure supplying the motor at the fixed point did not exceed 5 bars.

Coefficient of internal drag

This coefficient is by definition equal to

$$C_g = \frac{X_g}{q_2 \cdot A_2},$$

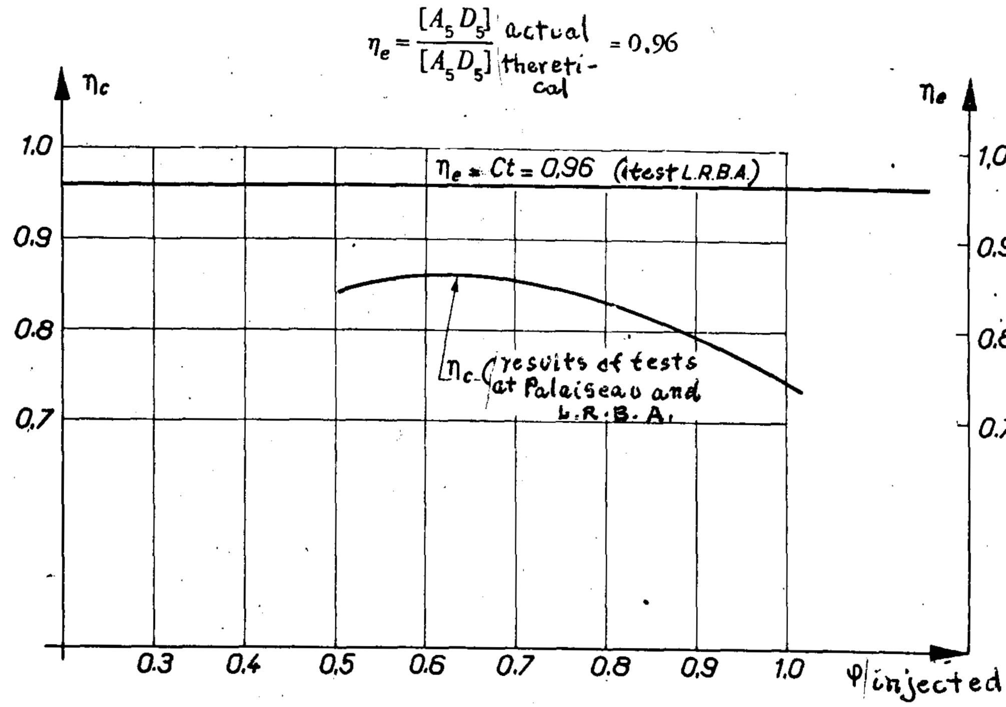

Figure 18. Combustion efficiency. Ejection efficiency.

q_2 being kinetic pressure at the end of the diffuser before combustion.

For the Staltex at the LRBA tunnel, and in simulated combustion (mechanical, nonthermal obstruction) there was obtained

$$C_g \simeq 4$$

This overall drag coefficient includes drag of the subsonic diffuser and drag of injectors and flame holders.

We note that this internal drag can be expressed approximately by the equation

$$\eta_g = \frac{Pi_2}{Pi_1} = 1 - 0.7 \, C_g \, M_2^2$$

where M_2 is the Mach number in the section under consideration, the number varying with combustion level and flight speed.

For Stataltex this load loss is always less than 6 percent.

External drag

Figure 19 presents the coefficients of aerodynamic drag of the Stataltex as a function of Mach number and flight altitude.

This graph results from the theoretical calculation and tunnel tests.

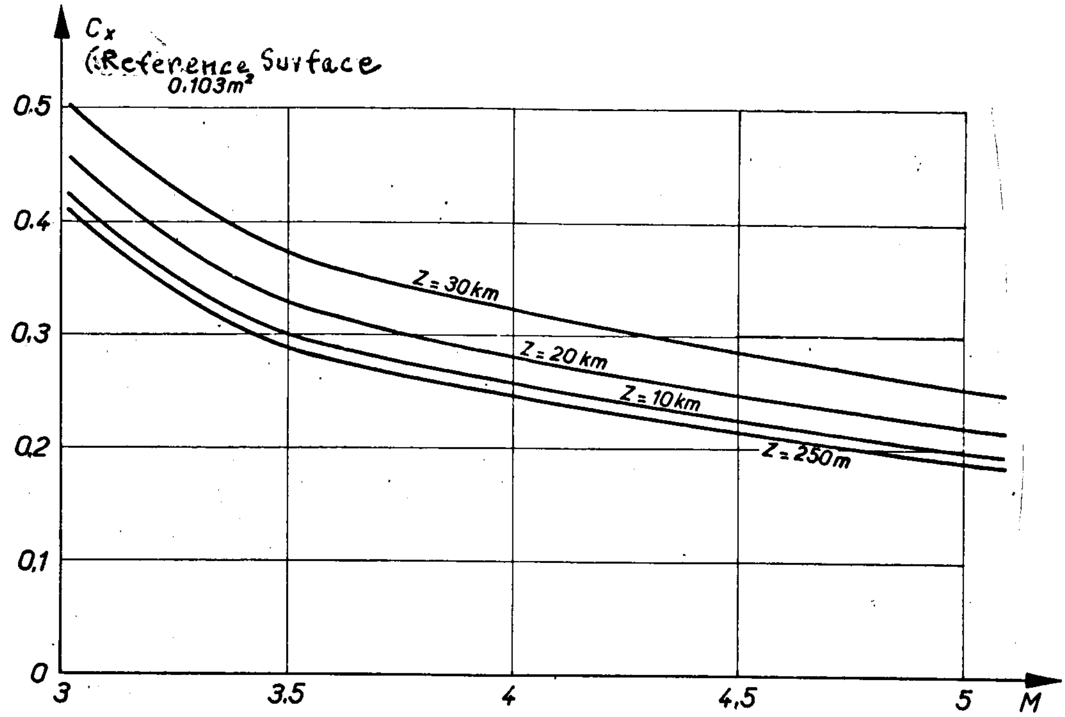

Figure 19. Drag coefficient.

Air intake

It is isentropic, adapted to $M_o = 3.5$. /23

Figure 20 presents its characteristics established in the wind tunnel: efficiency, flow coefficient and pumping limit.

III. 2.1. Conventional thrust deduced from the firing and from theoretical predictions

We recall that the conventional thrust of a ramjet is defined by:

$$P = [A_5 D_5] - [A_o D_o] - p_o(A_5 - A_o).$$

Knowledge at each instant of the following values makes it possible to calculate conventional thrust

- altitude, speed of flight and external conditions deduced from meteorological soundings,
- flow of injected fuel
- efficiency of the ejector and of combustion as well as use of the enthalpy fuel: air mixture diagram.

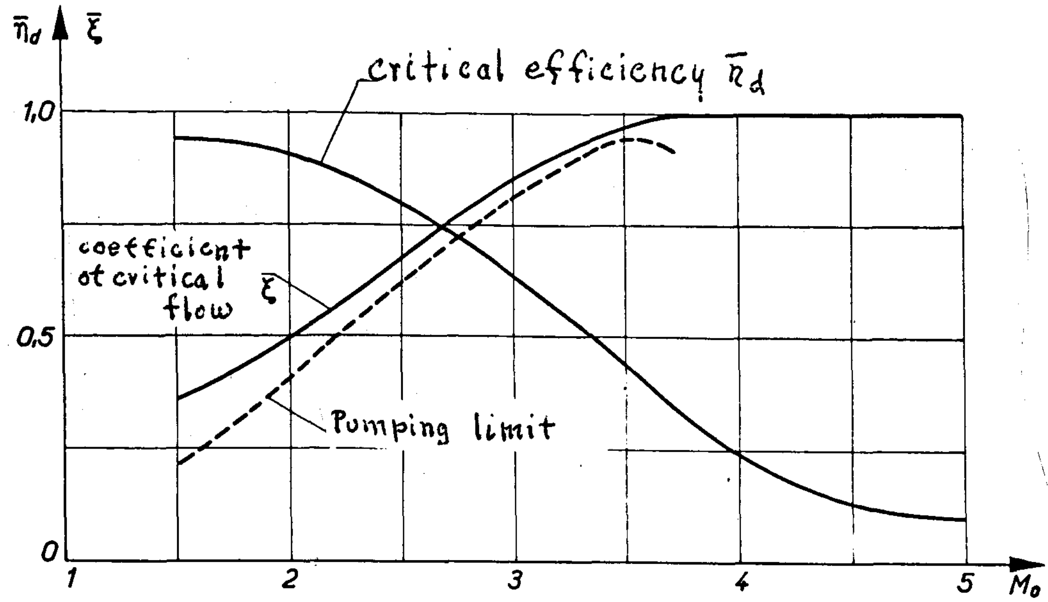

Figure 20. Characteristics of air intake rep 293 tests by LRBA and CEP.

The thrust value thus established is then compared with that deduced from flight accelerometer data, corrected for theoretical drag and weight

$$P = m(\Gamma + \sin\vartheta) + X$$

is accelerometer data.

The results of this analysis are presented in Figure 21 and relate to firings 02, 05, 06, 07, 08, 09. They show: /24

- the great flexibility of the engine whose measured in-flight thrust varied between 2000 and 100 daN, allowing a maximum acceleration of the order of 3G (see figure 15)
- the good agreement between predictions and firing. The deviations are no more than 5 percent when the thrust is greater than 200 daN. At the end of propulsion, at 30 km altitude, this discrepancy may reach 10 percent (as in firing 05): thrust is then of the order of 100 daN.
- the observed discrepancy during the first seconds of free flight of firing 06 is attributable to the subcritical functioning of the air intake at the start of the trajectory. Workup did not take this operational state (increased drag, reduced flow coefficient) into account on the general balance.

III. 2.2. Specific impulses deduced from the firings

The conventional specific impulse (in sec) is expressed as /25

$$I(s) = \frac{\mathcal{P}}{\dot{m}_k \cdot g}$$

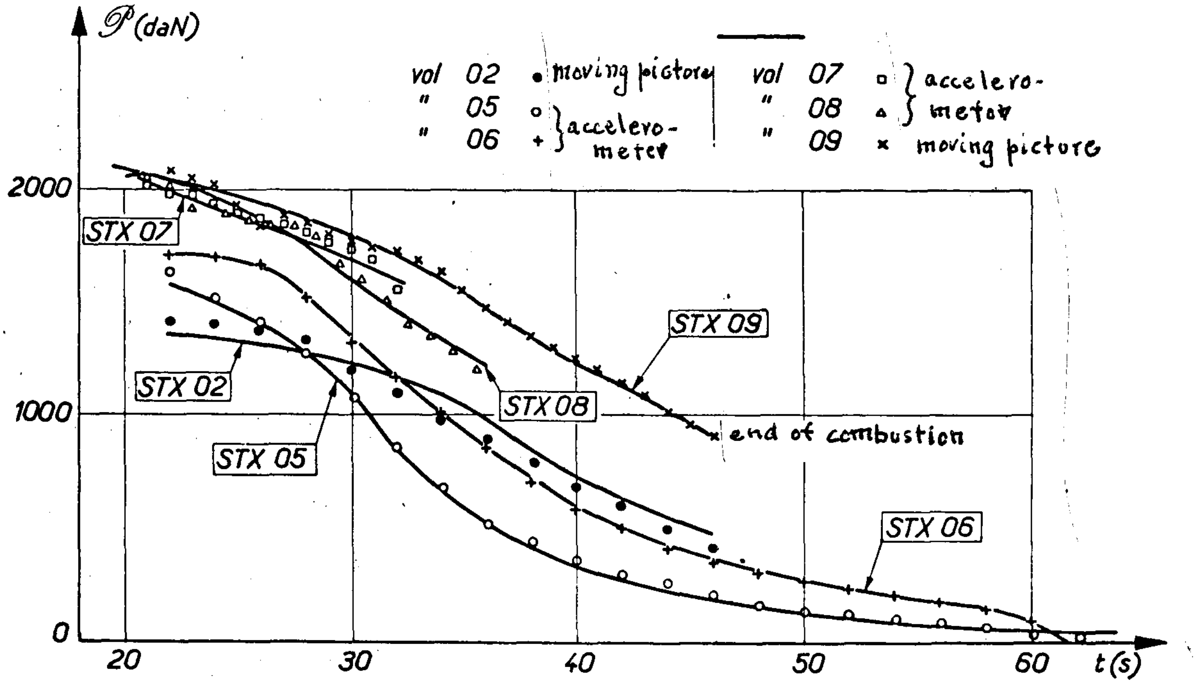

Figure 21. Comparison of conventional thrust (in flight and theoretical).

In figure 22 the specific impulses deduced from workup of data from firings 05, 06, 07, 08, 09 are presented as a function of speed of flight. Spread between firings does not exceed $\pm$ 5 percent.

This spread takes into account
- errors of measurement
- slight variation of specific impulses as a function of the fuel-air mixture burned which varied from flight to flight.

In figure 23 the specific impulses relating to firing 06 are presented together whth those deduced by two methods of calculation of conventional thrust (III, 2.1.)

The values thus obtained are compared with theoretical values corresponding to Stataltex with combustion yield unity, and then with that of a hypothetical optimal ramjet

$\varphi = 1$, $\eta_c = 1$, $\eta_e = 1$, $p_5 = p_o$, $\eta_k = 0{,}94$ (Kinetic yield of the air intake).

In connection with this investigation it may be noted that /26
- the actual specific impulses in flight are in agreement with predictions (refs. 1 and 2)
- the combustion efficiency of the Stataltex chamber entails a loss of about 15 percent of specific impulses

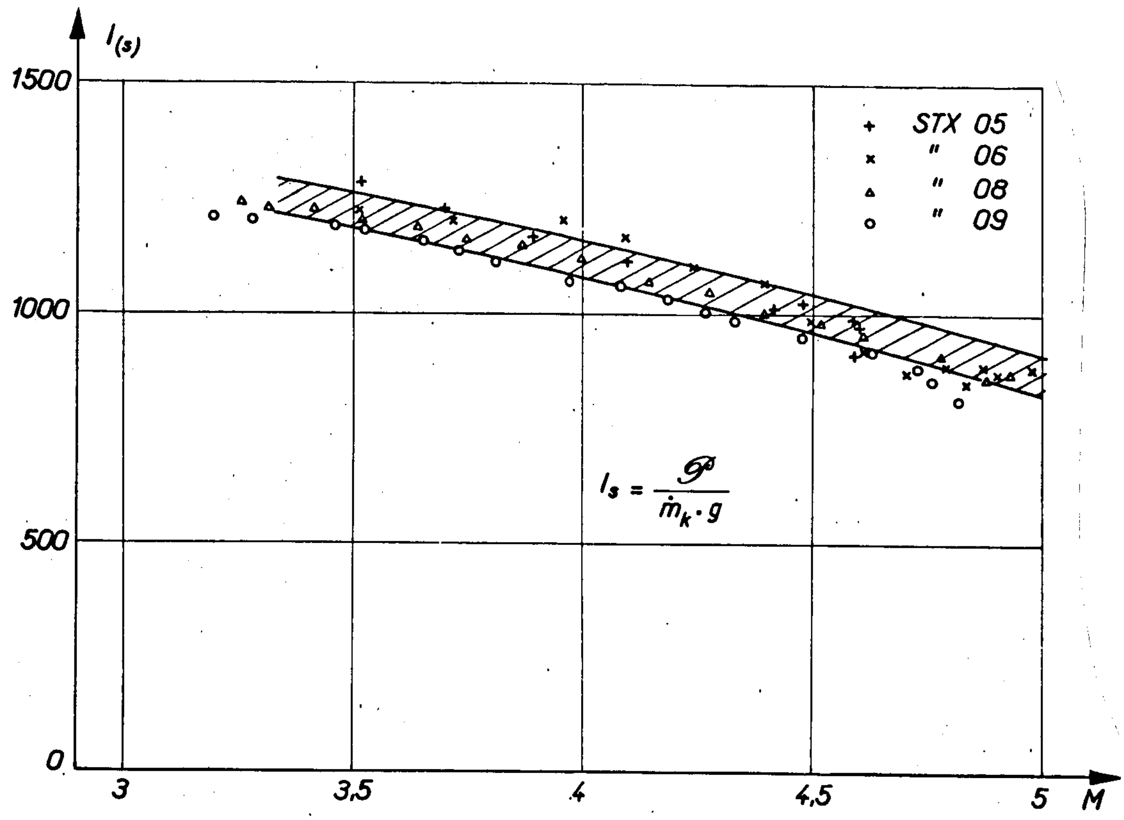

Figure 22. Specific impulse in flight.

- the nonadaptation of the air intake and the ejector reduces performance by 20 percent.

Nevertheless the actual specific impulses remain close to 1000 seconds at Mach 5.

III. 2.3. Internal pressures

All the Stataltex missiles were equipped with identical pressure sensors, located in the same section of the internal diffuser.

The value of this in-flight measured pressure was compared with the theoretical as a function

- of injected flow of kerosene
- of theoretical efficiency of combustion.
- of characteristics of air intake

From the examination of figure 24 it appears that

- the internal flight pressures varied between 11 and 0.25 bars, i.e., the level of modulation of thrust reached 40/1;

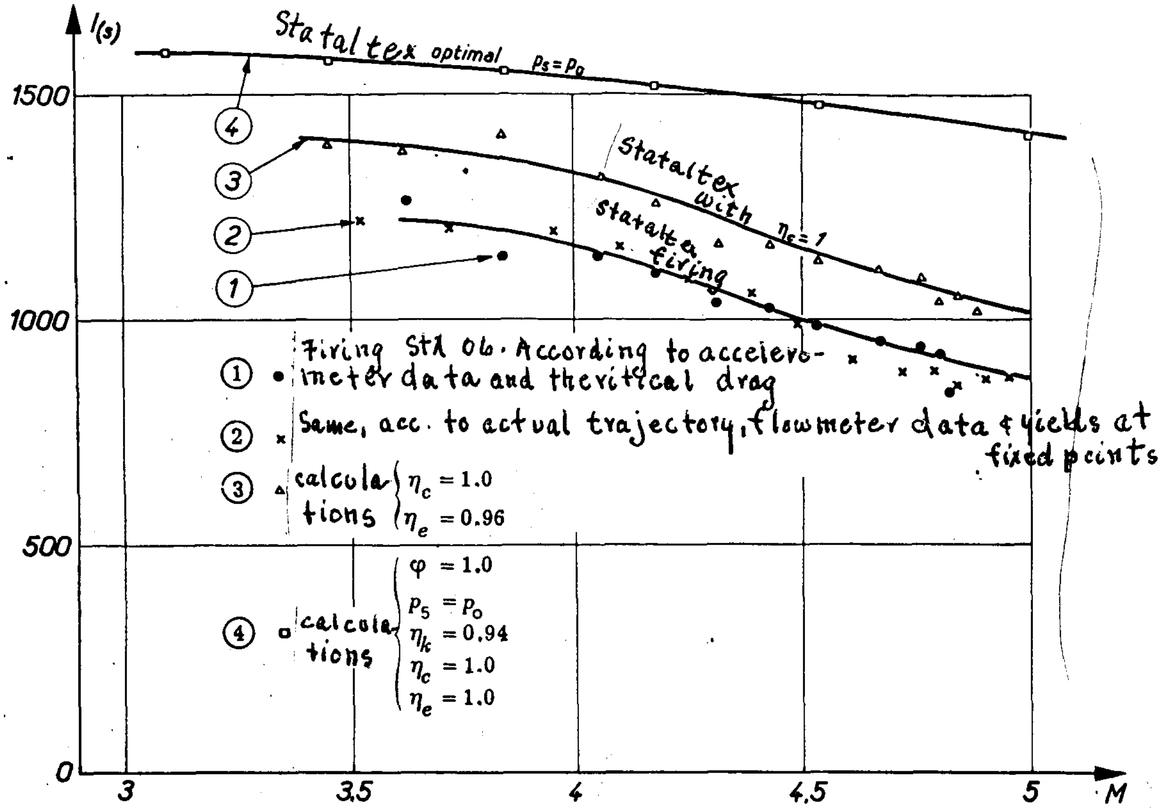

Figure 23. Comparison of specific impulses (flight and theoretical) STX 06.

- the results measured in flight and those furnished by theoretical calculation are close (difference of the order of 2 percent for the highest pressures, which value is within the range of inaccuracy of the pickups);
- differences are generally somewhat higher during the first seconds of free flight (uncertainty concerning coefficient of flow in the range of adaptation of the air intake i.e., $M_o \simeq 3.5$. This difference does not exceed 3 to 4 percent.
- for low internal pressure values (case of end of propelled flight of missile 05) the imprecision of the sensors--which were not adapted for this range of measurements makes any workup of data illusory.

Note

The measurement of internal pressure p_{i_2} makes it possible practically to determine the value of output dynalpy [momentum-flow, A5D5] of the ramjet, since the Stataltex ejector is calibrated at the fixed point. /27

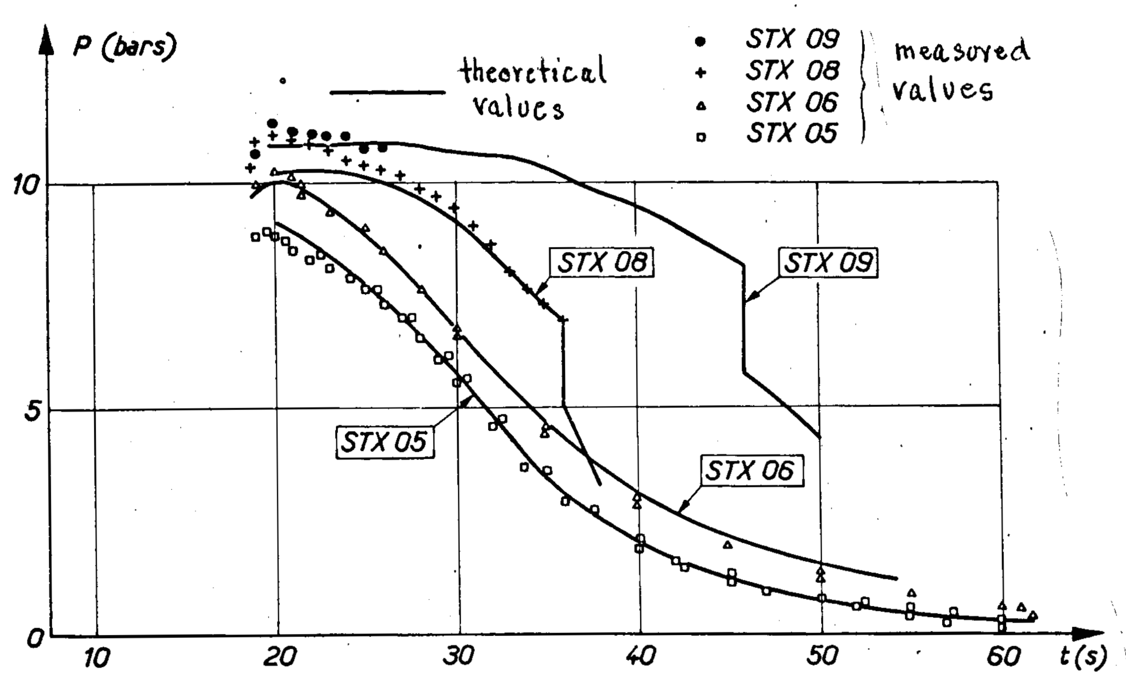

Figure 24. Comparison of internal pressures (in flight and theoretical).

An imprecision of 2 percent on the value of internal pressure p_2^i is expressed by an uncertainty of 2 percent with reference to output dynalpy. The following table shows the resulting indetermination with reference to conventional thrust

M_0	3	4	5
$\frac{\Delta \mathcal{P}}{\mathcal{P}}$ (%)	6	8	10

It may be noted that the direct calculation of conventional thrust led to equivalent results. It appears that the maximum errors in determination of the Stataltex in-flight thrust are below the values indicated above.

III. 3. Range of flight explored

The range--speed, altitude--explored in the course of the ten Stataltex firings appears in figure 25.

The kinetic pressures as well as the high temperatures outside and /28 inside the combustion chamber subjected the missiles to considerable mechanical

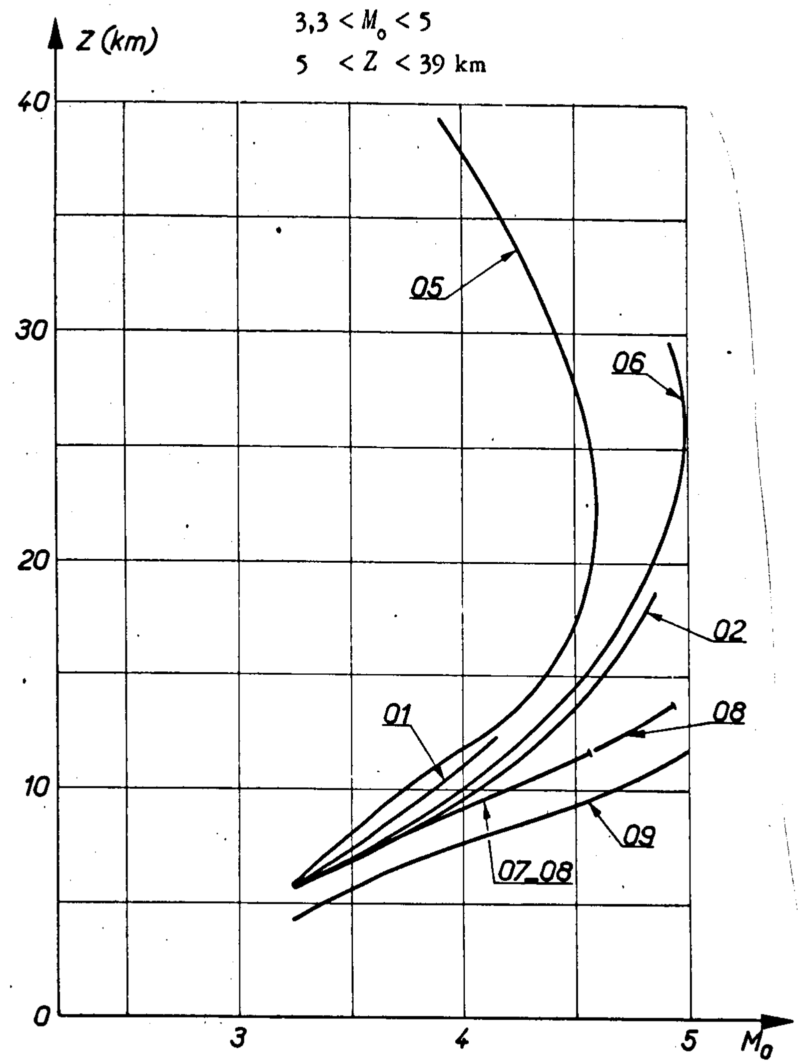

Figure 25. Range of flight investigated with ramjet propulsion.

and thermal stress. The table below indicates the order of magnitude of certain characteristic values

M_0	q_0 (bars)	p_{i_2} (bars)	T_{i_2} (°K)	T_{i_4} (°K)
3,3	4,5	9 – 11	820	1 700
4	2 – 4	7 ÷ 11	990	2 300
5	0,2 – 3,5	0,35 ÷ 8	1 260	2 700

III. 4. Flight dynamics

III. 4.1. Spread of the trajectories

As indicated in II. 1.2, the inclination of the trajectory at separation of the two stages must be determined with maximum precision, since the performance of the missile is very sensitive to this parameter.

Precautions had been taken to limit this spread

- tolerances on the duration of combustion of the Stromboli booster (II. 1.2); Figure 19 shows the spread obtained after the ten Stataltex firings[1]
- corrected launcher inclination as a function of aerological sounding (modulus and direction)
- geometric control of the missile with close tolerances

General alignment at ± 2 mm (total length: 10 m)
Alignment of airfoils at ± 3'.
Thrust vector oriented at ± 2'.

Figure 26 indicates the spread of positions taken at separation, with the consideration of precautions. We recall that the aimed inclinations, of the order of 30°, required launch angles close to 60°.

A percussion at departure from the launcher is at the root of the /29
main part of the spread of trajectories, as shown by a study of the dynamics of the launcher effected after firing 06. For firings 07, 08 and 10, effected from a launcher that had been made more rigid, the spread did not exceed 3°.

III. 4.2. Load factors

Maximum values, 2G for composite flight and 1G for flight of the ramjet alone, conform to predicted values, taking into account the kinetic pressures that were encountered (III. 3.) and the size of the stabilizing airfoils.

Configuration	$C_{zi} A$ (m^2/radian)
Composite at start	12
Ramjet at separation ($M_o = 3$)	1,7

IV. In-flight behavior of the ramjet

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[1] Only firings 06 and 09 are beyond the ± 1.5 percent range of spread, which is explained by local temperature conditions at the time of firing.

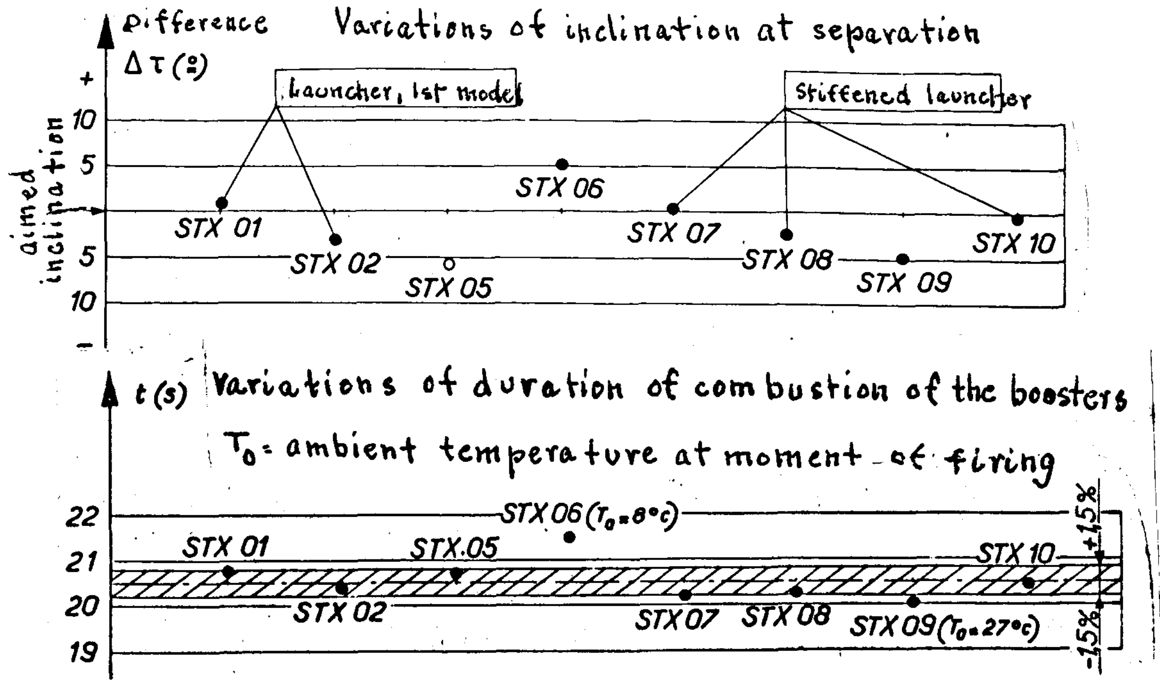

Figure 26.

IV. 1. Functioning of the air intake

Control of the missiles was effected in such a way as to ensure a supercritical operational state of the air intake. Figure 27 shows by way of example the levels of recompression (efficiency) in the case of firing 06.

The subcritical operation of the air intake caused the failure of firings 03 and 04. We recall that in these firings the subcritical operational state was fortuitously established, the actual efficiency of the air intake at $M_o = 3.5$ being less than that deduced in tunnel tests.

An interesting result obtained in the Stataltex study is the beneficial use of an air intake in superadapted operational state.

Since coefficient of flow ϵ is maximal beginning at $M_o = 3.5$, the shockwave issuing from the point penetrates to the inside of the shell, beyond that speed. /30

This operational state with maximum coefficient of flow from $M_o = 3.5$ makes it possible to obtain high thrust coefficients along the entire trajectory with a fixed geometry, additive drag being zero.

Figure 28 relates to missile 06.

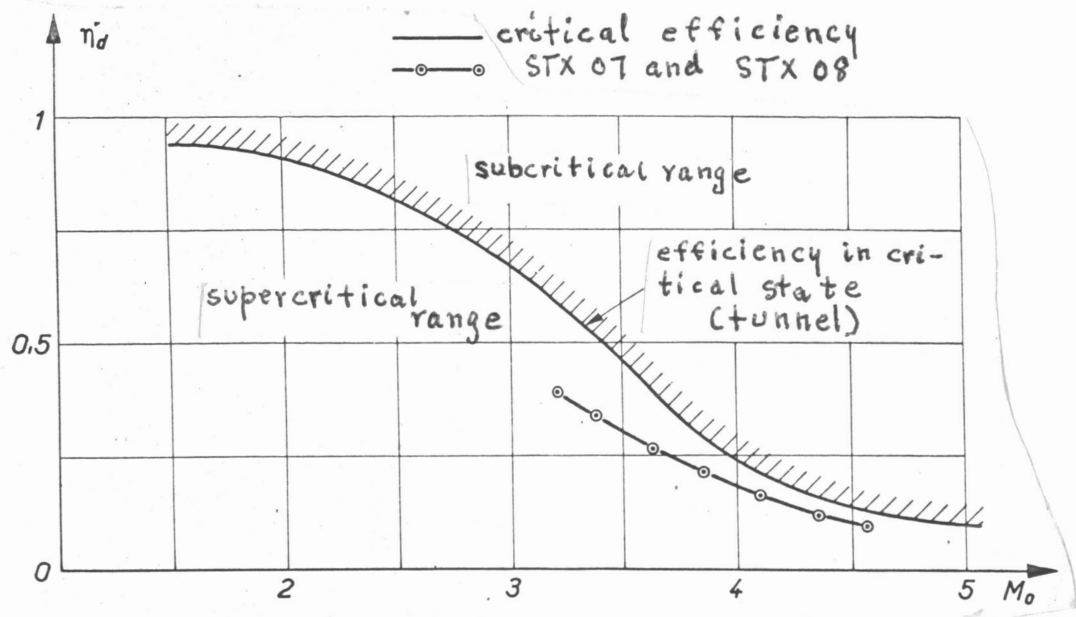

Figure 27. Operation of air intake in flight Rep. 293.

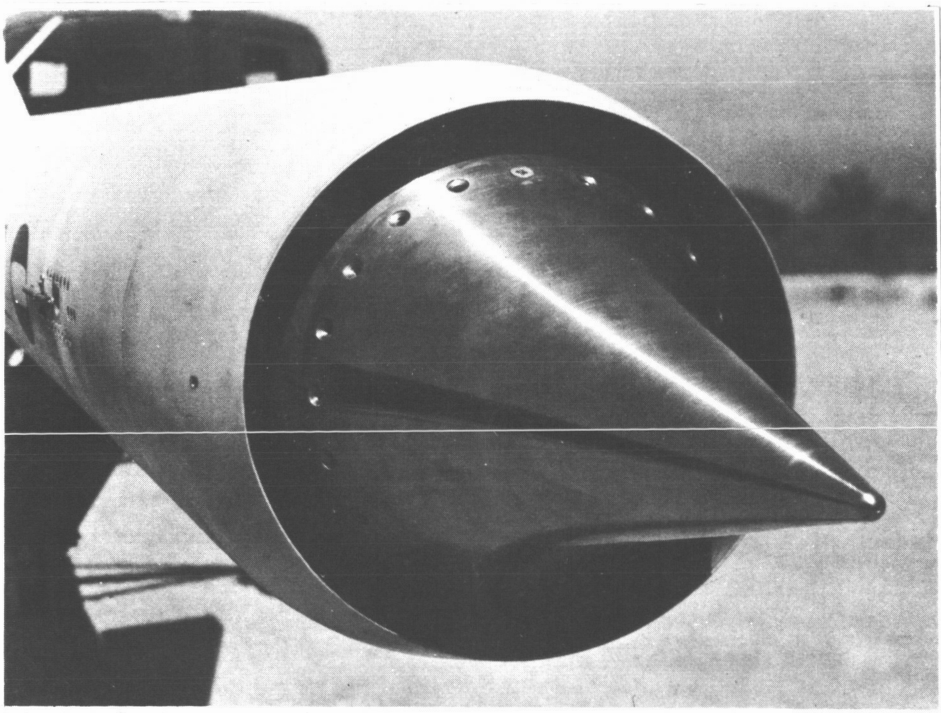

Figure 28. Air intake.

IV. 2. Behavior of the combustion chamber

During ten Stataltex firings, the air-fuel mixture in flight varied between $0.3 < \varphi < 1.2$ and the operation of the chamber was always satisfactory. Ignition and power of the engine conformed to the program.

In contrast, the thermal behavior of the flame tube sometimes limited the duration of the test. Bophénal protection made it possible to attain Mach 5 at 25 km altitude, but it was necessary to design more effective Orthostrasil protection to achieve performance at higher kinetic pressure (flight at 12 km altitude)

Figure 29 indicates heat fluxes and behavior of the Orthostrasil (carbonized layer) in a simulation test of the Stataltex program at Mach 6 made on the ONERA test bench at Palaiseau.

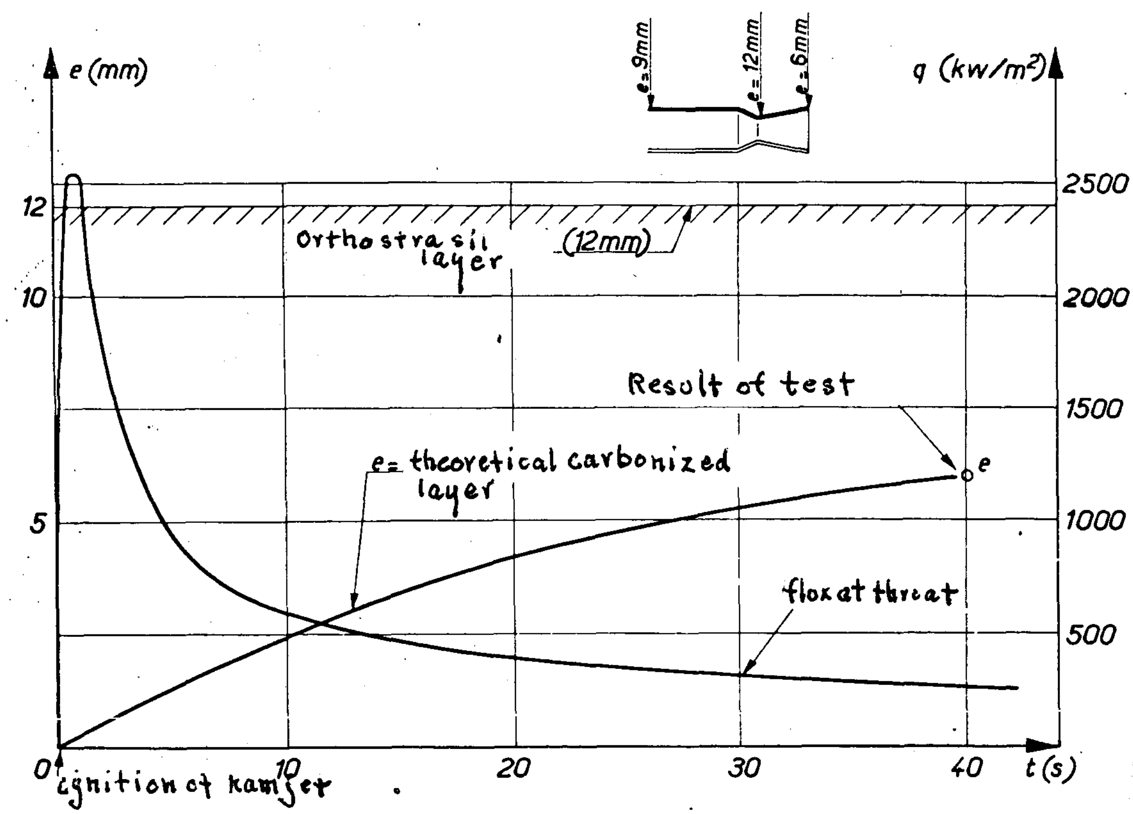

Figure 29. Heat flux at throat of "Orthostrasil" ejector (simulation test at Palaigeau) carbonized layer e (at throat)

This Orthostrasil solution seems valuable for the protection of a first stage combustion chamber of an atmospheric engine (accelerating engine with consumable chamber).

IV. 3. Thermal behavior of the cellule

During flight conditions of Stataltex at Mach 5, the temperature of the central body reaches 800°C and that of the hull 700°C (fig. 30). These temperatures are practically those of equilibrium for a flight at M_o = 5 and 25 km altitude. /32

These cellules fulfilled the following mechanical specifications:

- possibility of relative dilation between central body and hull
- central body pressure-balanced
- utilization of NS 30 UGINE refractory steels without thermal protection, the thickness of the sheet being selected after a series of rapid extrusion test. In flight conditions, the level of permissible extrusion was 0.5 percent for 60 seconds test.
- rigorous seal of the coupling elements.

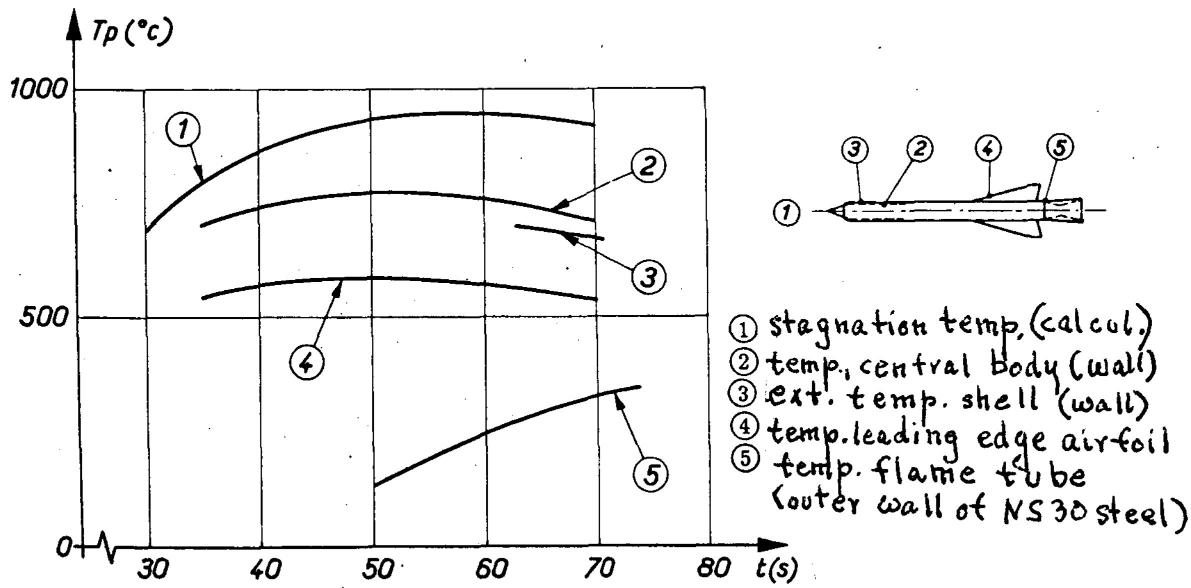

Figure 30. Development of structure temperatures (in-flight measurements).

V. Conclusion

The Stataltex flights confirmed the possibility of the fixed geometry ramjet used in the range Mach 3 - Mach 5.

The attained performances, about 1000 seconds of specific impulses at Mach 5, are in agreement with theoretical predictions. An in-depth work on development of the combustion chamber would have allowed improvement of these performances by about 150 seconds.

Of eight missiles launched at Ile du Levant, seven furnished data suitable for workup, and four flew at Mach numbers close to 5. The explored range of flight between 10 and 37 km altitude represents approximately the range of development of possible high speed aircraft or atmospheric satellite booster.

The measurements effected in flight are of good quality and allow establishment of a propulsion balance that cuts by more than 10 percent the predictions for flight deduced from stationary tests.

Since these missiles were not guided, these performances were effected on trajectories with very high kinetic pressure (4 bars at Mach 3), the internal pressures attaining 10 bars and longitudinal accelerations of 3G.

Such performances were possible only because of the isentropic type air intake, operating in superadaptation beyond Mach 3.5. This solution allows an interesting compromise, the entrance and exit geometries of the engine being fixed.

The Stataltex study thus indicates that a fixed-geometry ramjet with superadapted air intake performs in an interesting manner. A similar configuration is worth considering in establishing a pioneer project for an aerospace launcher.

Finally, on the technological level the Stataltex flights demonstrate the worth of thermal protection of the Orthostrasil type to ensure short but very demanding missions using atmospheric propulsion (case of flight at Mach 5, altitude 12 km, duration 1 minute).

If modified and improved, the Stataltex missle would be capable of performing above Mach 5. Studies and simulation tests effected in the Palaiseau laboratories have shown that this missile could then accelerate to Mach 6, the cellule having generally been designed for this range of speed.

Two attempts to carry the performance of Stataltex beyond Mach 5 /33 were unsuccessful, because the ramjets were not inserted with the desired precision in the narrow flight corridor which is indispensable for attaining such a speed. The development of this study would necessitate use of a guidance device.

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